Non-Rigid Registration to Capture Optic Nerve Head Variability

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Abstract. Glaucoma causes variations of the optic nerve head (ONH). We propose an approach to describe the inter subject variability of the ONH by dense deformation fields produced by non-rigid registration. Non-glaucoma but acquisition related variations are eliminated in a pre-processing step. Standard non-rigid registration was extended by a radial smoothing regularizer to preserve the ONH natural circular appearance and to enforce a physiological suitable mapping. The proposed approach captures successfully ONH variations.

1 Introduction

Glaucoma is one of the leading causes for blindness as it induces a degeneration of retinal nerve fibers. The occurence of the disease is also accompanied by changes of the optic nerve head's (ONH) appearance. Based on a quantitative characterisation of the ONH several glaucoma indices were developed [1]. However, most of these techniques rely on geometric measurements or parameters of the ONH such as diameter or area. From our point of view, the established techniques only utilize a sparse characterization of the ONH.

Thus, we propose to describe the inter subject variability of the ONH by dense deformation fields produced by non-rigid registration. It represents the first step towards high resolved statistically modelling of ONH variability.

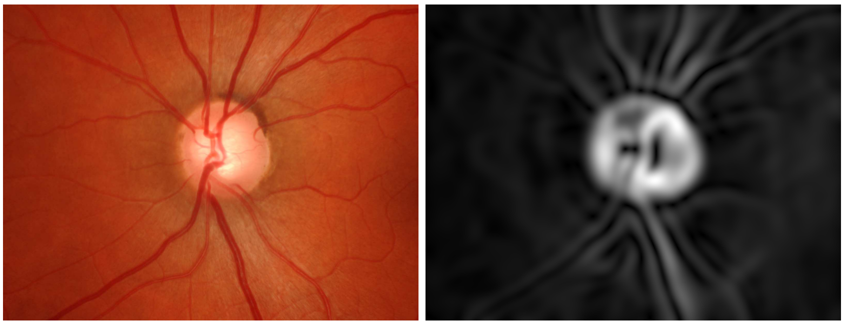
To the authors' knowledge existing registration approaches on retinal images are mostly used for mapping intra subject images in longitunal studies or mosaicing-like methods. There are several feature based approaches utilizing landmarks out of the segmented vessel tree to map template and reference image. The mapping transformation is represented by a stand-alone quadratic model [2] or by an affine model that can be refined by a quadratic model if necessary [3,4]. Region based approaches are used to e.g. reconstruct the ONH depth information from stereo images [5]. Different metrics and optimization methods for rigid registration are compared by Karali et al. [6].

2 Material and Methods

The proposed registration approach is divided into two steps. (i) Acquisition dependent translations, not related to the disease are excluded by a previous rigid registration. (ii) The variability of the ONH is captured by non-rigid registration that additionally accounts for a natural circular mapping and the individual vessel structure.
In the following the used state-of-the-art metrics and registration techniques are based on Modersitzki [7].

2.1 Elimination of translation variations

The rigid registration is applied on gradient magnitude fundus images. This representation emphasizes the ONH as region of interest and suppresses the individual vessel tree in case of large filter support and is less sensitive to luminosity variations (Fig.1).



(a) (b)

Fig. 1. Example for the preprocessing before applying rigid registration. The gradient magnitude image (b) computed from the input image (a) emphasizes the ONH as region of interest.

2.2 Capturing of the papilla shape variability

In order to capture the inherent ONH variability, we apply an adapted non-rigid registration approach. It is extended by a regularisation term approving radial deformations to ensure a physiological mapping of the corresponding ONH sectors. Since the vessel tree is highly individual like a fingerprint it is masked out during the calculation of the distance measures. The registration problem is formulated as an constraint optimization problem:

$$\min_{\mathbf{U}} J = D(\mathbf{R}, \mathbf{T}_{\mathbf{U}}) + \tau S(\mathbf{U}) \tag{1}$$

with the deformation field $\mathbf{U}$ minimizing the distance D between the reference image $\mathbf{R} \in R^{n\times m}$ and the deformed template image $\mathbf{T_U} \in R^{n\times m}$ while constrainted by a smoothing factor S.

We additionally developed a so called *radial smoothing* S_{RS} to regularize the registration to favor a circular growing or shrinking of the ONH. The introduced weighted radial term measures the deviation of the deformation's directions to the radial directions originated in the ONH center (c_0, c_1):

$$S_{RS}(\boldsymbol{U}) = \sum_{i=0}^{m-1}\sum_{j=0}^{n-1}\left(\|\boldsymbol{u}(i,j)\|_\epsilon^2 - \left(\frac{\boldsymbol{u}^{\mathrm{T}}(i,j)\boldsymbol{r}(i,j)}{\|\boldsymbol{r}\|_\epsilon}\right)^2\right),\ \boldsymbol{r}(i,j) = \begin{pmatrix} i-c_0 \\ j-c_1 \end{pmatrix} \quad (2)$$

with $\|.\|_\epsilon$ the modified Euclidean norm to prevent the result of being zero. S_{RS} preserves the circular shape of the ONH and prevents unnatural results like surface-water-like appearance.

3 Results

The registration was evaluated on 60 randomly selected image pairs with a size of 1600×1216 for each image. As gold standard, we used the translation between the ONH centers and the segmented OHN rims after registration automatically determined by an ONH segmentation technique [8].

3.1 Rigid registration

As distance measures for the rigid registration we applied "Sum of Squared Distances (SSD)" and "Normalized Correlation (NC)" optimized by "Regular Step Gradient Descent Optimizer" to build a translation model. Both metrics are fast and sufficient for mapping two blob-like shapes of nearly similiar intensities.

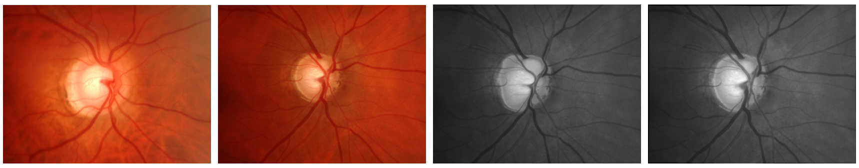
Initially, only 53.33 % of the pairs showed an ONH distance lower than 150 pixels. This rate could be improved up to 76.67 % for SSD and 78.33 % for NC. Overall, the rigid registration on gradient magnitude filtered fundus images showed a reasonable compensation of translation variations.

3.2 Non-rigid registration

For the the non-rigid registration, we evaluated "Sum of Squared Distances (SSD)" as mono-modal and "Mutual Information (MI)" as multi-modal metric to incorporate the impact of the luminosity inhomogeneities and the non-standardized intensities.

Fig. 2 shows an example of a deformed template image using SSD. It illustrates that the additional radial regularization is able to preserve the natural circular shape of the ONH in contrast to the bumped ONH in case of stand-alone SSD.

For a quantitative evaluation, we compared the automatically determined radii of the ONH rims of the reference and the deformed template images. This



(a) (b) (c) (d)

Fig. 2. Reference (a), template (b) and result of non-rigid registration using **sum of square differences stand-alone** (c) and in combination with **radial smoothing** (d) showing that the radial smoothing is able to preserve the natural circular optic nerve head appearance.

criteria is independent from the optimized distance measure. Table 1 shows the non-rigid registration utilizing SSD as distance measure results in the lowest radii difference average of around 34 pixels. As the SSD in combination with radial smoothing additionally decreases the standard deviation from 38.0 for stand-alone SSD to 33.1. We consider this configuration as most reliable.

Table 1. Average error and standard deviations for **radius differences** between reference and deformed template ONH in 60 randomly chosen image pairs. In contrast to **Mutual Information** (MI), the **sum of squared differences** (SSD) in combination with the proposed **radial smoothing** (RS) produces the lowest average error and standard deviation to be considered as a reliable technqiue for ONH variability capture.

Metric	Average error	Standard deviation
Initial	45.08	39.46
MI	41.95	38.97
MI + RS	43.60	40.69
SSD	34.52	38.00
SSD + RS	34.52	33.14

4 Discussion

The rigid registration is able to reduce the inter ONH distances. But the quality of the input images, mainly luminosity homogeneity, is still important. The gradient based preprocessing emphasizes the ONH only at a border area, if the luminosity variations are too strong around the papilla, which results in less reduced distances after the registration. Nevertheless, translation variations can be reduced sufficiently for the ONH variability capturing.

The results of the non-rigid registration have to be considered as a trade-off between preserving the natural appearance of the template ONH and adapting the shape of the reference and the template ONH. After a visual inspection of the results SSD and MI stand-alone tend to produce results like surface-water-like appearances inside the ONH area or unnatural formed ONH borders.

Overall the proposed registration pipeline is able to reliable capture inter subject ONH variability as it clearly reduces the average difference between the ONH diameters of the reference and the deformed template images. Only due to the radial smoothing, related ONH sectors are physiological correctly matched and the deformed ONH retains its natural appearance.

This technique is able to densly describe the ONH variability by deformation fields and can be considered as the first step towards a highly resolved statistical deformation modeling to gain new insights to e.g. the glaucoma disease.

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